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The influence of shielding gas and heat input on the mechanical properties of laser welds in ferritic stainless steel

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Abstract

Laser welding of ferritic steel in normal atmosphere gives rise to weld embrittlement and poor formability. This paper demonstrates that the addition of an argon gas shield to the welding process results in tough, formable welds. Post weld heat treatment and microscopic analysis has suggested that the poor ductility of welds produced without a gas shield is, to some extent, the result of the presence of oxides in the weld metal.

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Keywords: Laser welding; Ferritic stainless steel; Shielding gas

1. Introduction

Ferritic stainless steel is often used as a cheaper alternative to Austenitic stainless grades. The stress corrosion properties of ferritic stainless steels are actually better than those of austenitic stainless steels and they are therefore used for the manufacture of boilers, water heaters and automobile exhaust systems (Outokumpu Oyj, 2010, Kyröläinen and Lukkari, 1999). Ferritic stainless steel grades do not have the excellent weldability of their austenitic counterparts, which can be successfully laser welded without a shielding gas in order to achieve the good mechanical properties. The use of shielding gas improves the corrosion properties of the weld area generally.

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When AISI grade EN 1.4512 (STS 409L) is welded using Gas Tungsten Arc (GTA), martensite is formed in the weld area due to nitrogen absorption from the different content of Ar + N2 back shielding gas when the N2 content is increased. When laser welding this material without the argon back shielding gas shield, the nitrogen content of the weld is increased further due to the increased temperatures in the weld zone compared to the GTA process (higher melt surface temperatures result in increased absorption). The use of Argon as the shield gas decreases the nitrogen content and therefore reduces the hardness of the laser weld (Lee et al., 2008 and Nakao et al., 2008).

According to Lakshaminarayanan laser welds of AISI 409M type ferritic stainless steels carried out with argon as a shielding gas had good ductility and formability at room temperature although the hardness of the weld was significantly higher than the base material as a result of rapid solidification (Lakshaminarayanan et al., 2012).

When welding with a CO2-laser the shielding gas is also used to remove the plasma plume which can absorb the laser beam at this wavelength, but in case of Yb:YAG laser beam the absorption by the plasma plume is minimal.

The aim of this present study was to investigate the ductility of ferritic stainless steel laser welds produced by using different welding energies and shielding gas arrangements.

2. Experimental Work

1.5 mm thick EN 1.4521 ferritic stainless steel was used in this study. This kind of stainless steel is alloyed with molybdenum, which makes it acid proof. Titanium and niobium are used as stabilizing elements in order to bind the interstitial elements Nitrogen and Carbon to stable Ti- and Nb- carbonitrides. Otherwise free interstitial elements in the matrix of the microstructure could create a brittle martensitic structure in welds. As a result of its higher Cr content, ferrite is more stable in EN 1.4521 than in EN 1.4512 (Balmforth et al., 1998). The Kaltenhauser ferrite factor (Kyröläinen and Lukkari 1999) for the EN1.4521 grade is 26.3 as compared to 12.3 for EN 1.4512. This indicates that the microstructure of a laser weld in EN 1.4512 material can contain martensite, but the microstructure of a weld in EN 1.4521 grade should be completely ferritic. The composition of the steel is given in table 1.

Table 1. Chemical composition of the EN 1.4521 type ferritic stainless steel grade

C %	**Si %**	**Mn %**	**P %**	**S %**	**Cr %**	**Ni %**	**Mo %**	**Ti %**	**Nb %**	**N %**
0.019	0.49	0.52	0.026	0.002	18.0	0.2	2.01	0.12	0.40	0.026

The mechanical properties of the base material are shown in table 2.

Table 2: Mechanical properties of the EN 1.4521 ferritic stainless steel grade

$R_{p0.2\%}$, MPa	**R_m, MPa**	**A 5, %**	**A 50, %**	**Hardness, HB30**
371	524	48	30	182

Laser welding of test samples was carried out using a Trumpf HLD 4002 diode pumped disk laser with a fiber diameter of 0.2 mm and focusing optics with a focal length of 300 mm. The collimation length of the optics was 200 mm and the beam parameter product was 8 mm*mrad.

This arrangement gave a focal point diameter of 0.3 mm. The root gas was blown into an enclosed space at the backside of the plate. The distance of the shielding gas nozzle from the surface of the plate was 1 mm. The shielding gas arrangements are shown in fig.1.

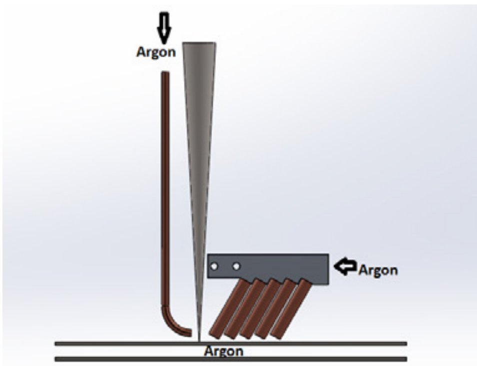


Fig. 1 The shielding gas arrangement.

The welding parameters of the tests are shown in table 3. (The energy input does not take account absorption and is thus greater than the real welding energy.)

The welds were heat treated at 750 °C for 2 hours in order to remove any possible martensite from the microstructure which may have been formed as a result of nitrogen absorption from the air. The tensile tests were carried out using a Zwick Tension test machine according to the DIN EN 10002-1 standard.

Table 3. Laser welding parameters

Weld ID	Power, kW	Speed, m/min	Focal point position, mm	Shielding gas Ar, l/min	Root gas Ar	Energy input, J/mm
E23 Air	3.00	8.0	-1	no	no	23
E23 Argon	3.00	8.0	-1	30	yes	23
E50 Air	1.25	1.5	-1	no	no	50
E50 Argon	1.25	1.5	-1	30	yes	50
E90 Air	1.95	1.3	+6	no	no	90
E90 Argon	1.95	1.3	+6	30	yes	90

Vickers hardness tests were carried out on a Shimadzu microhardness machine using a 200 g weight. The hardness profiles were measured one quarter of the thickness from the bottom and top side of the weld at intervals of 0,1 mm over the weld and into the base material.

Bending tests were made in order to reveal the formability of the weld. The bending tests were made at room temperature using a simple hand operated bending machine. The samples were bent along the weld line and the maximum bending angle was measured.

Erichsen cupping tests were carried out using a 10 mm punch ball. The test displacement was measured using MTS material testing equipment. The center points of the welds were aligned 3 mm from the center point of the forming area (see fig. 10). The punch speed was 0.5 mm/s in all tests.

The cross section figures were grinded, polished and electrochemically etched by using 60 % Nitric acid at 40 mA/cm2 current density. The microstructure figures and fracture figures (figs. 11-12) were made with a Keyence VHX 2000 E digital microscope.

3. Results

3.1. Tensile tests

All the tensile test specimens failed in the base material, as shown in fig.2, because the hardness and strength of the welds were higher than the base material. Therefore the results of the tensile tests were as for the base material (Table 2.). The tensile test results are shown in table 4.

Table 4. Tensile test results

	Rp0.2 MPa	Rm MPa	Ag %	A50 %
E 23 air	422	527	15	27
E 50 air	495	617	15	28
E 90 air	434	539	15	26
E 23 argon	429	534	15	15
E 50 argon	424	527	15	28
E 90 argon	412	513	15	25

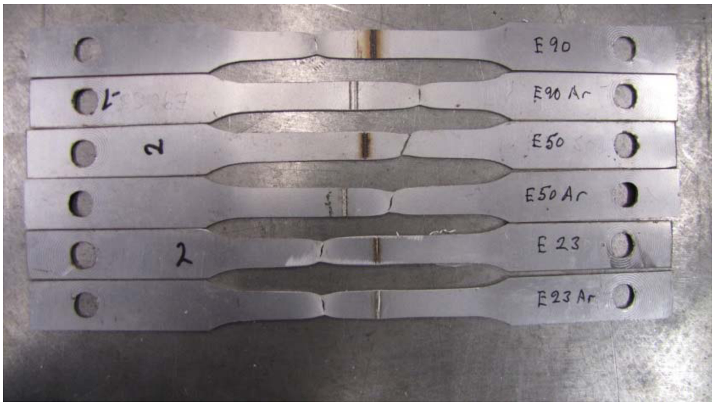


Fig. 2. The broken tensile test bars

3.2. Hardness tests

The hardness profiles of the different welds, with and without post weld heat treatment are shown in figs. 3-8. The results are the average of four measurements in each case.

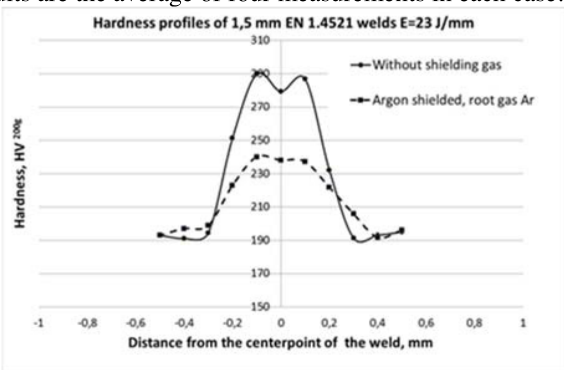


Fig.3 Hardness profile of 23 J/mm welds

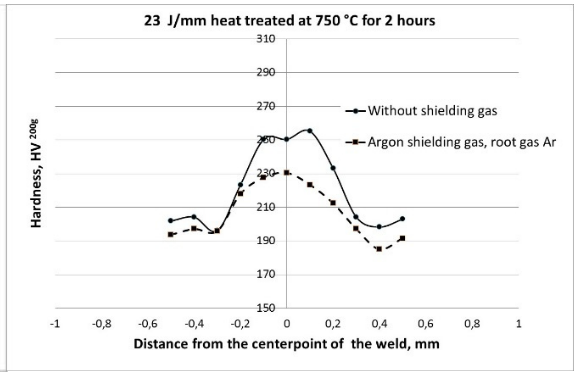


Fig.4 Hardness profile of heat treated 23 J/mm welds

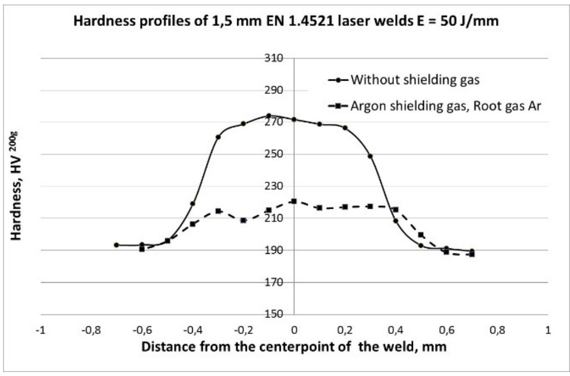


Fig.5 Hardness profile of 50 J/mm welds

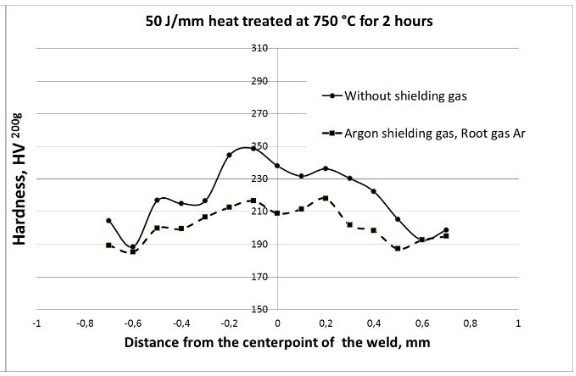


Fig.6 Hardness profile of heat treated 50 J/mm welds

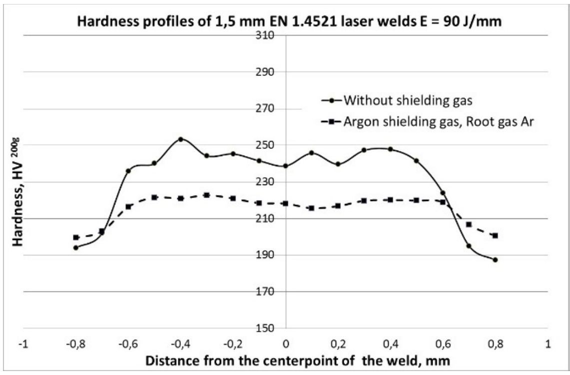


Fig.7 Hardness profile of 90 J/mm welds

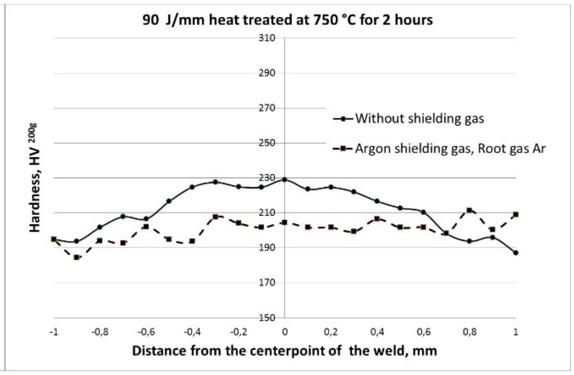


Fig.8 Hardness profile of heat treated 90 J/mm welds

3.3. Formability tests

3.3.1. Bending test

The bend test results are shown in table 5.

Table 5. The maximum bending angles of the laser welds as welded and after heat treatment (PWHT).

	Bending angle, °	PWHT Bending angle, °
E 23 air	8	68
E 50 air	180	180
E 90 air	6	45
E 23 argon	180	180
E 50 argon	7,5	36
E 90 argon	180	180

3.3.2. Erichsen cupping test

Typical results of the Erichsen tests are given in fig 9. Typical broken test samples are shown in fig. 10.

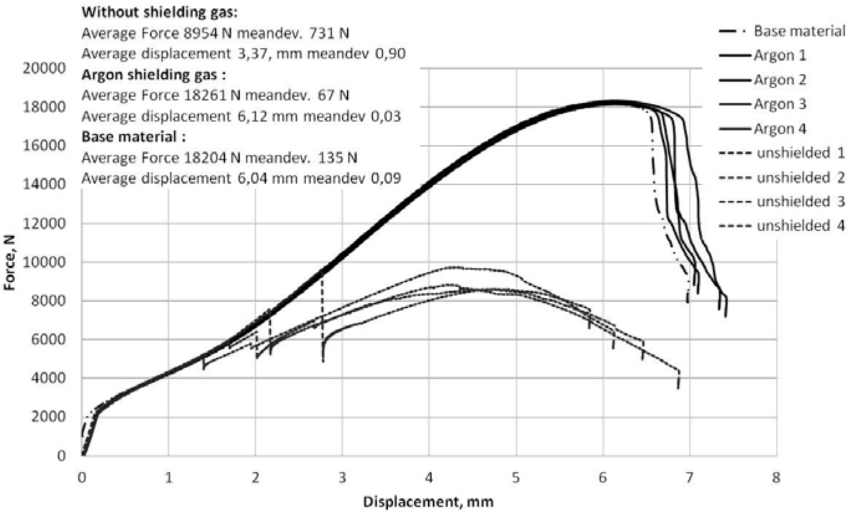
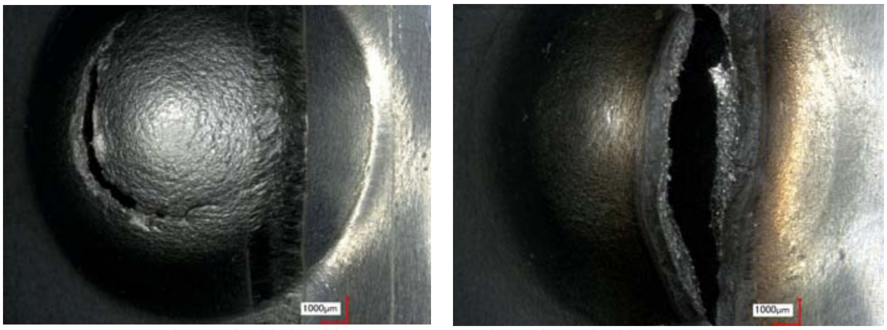


Fig 9. The Erichsen cupping test results of 1.5 mm ferritic stainless steel Ar-shielded and unshielded welds produced at a weld energy of 90J/mm.



a) Argon shielded weld *b) Without shielding gas*

Fig. 10. The Erichsen cupping test samples for laser weld samples E=90 J/mm, welded with and without Argon shielding.

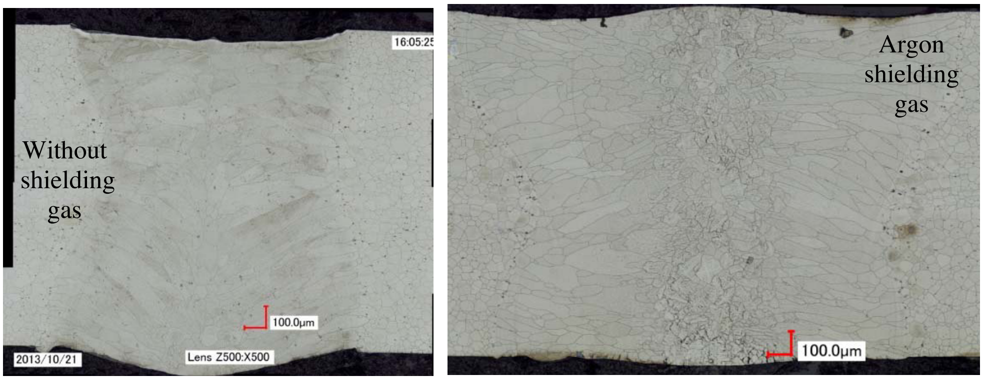


Fig 11 The cross section of the 90 J/mm welds without shielding gas and with argon shielding gas

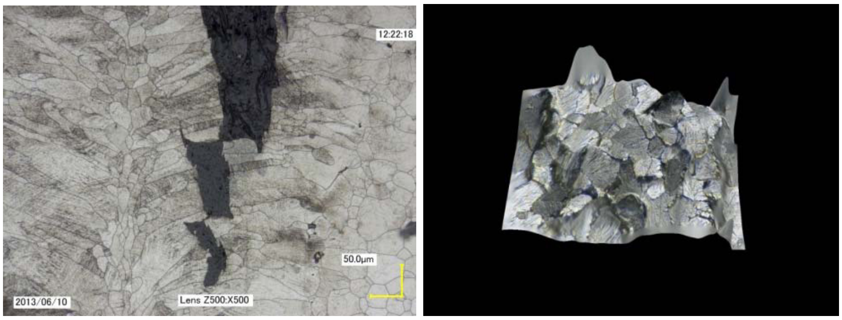


Fig. 12 Brittle cleavage fracture of unshielded EN 1.4521 weld at 8° bending angle (sample E23Air)

4. Discussion

4.1. Hardness

The hardness of the Argon shielded welds were 40-50 HV units lower than the welds without shielding gas in the case of the 23 J/mm and 50 J/mm welds. In the case of 90 J/mm weld the reduction in hardness was 20 HV units.

Post weld heat treatment of the welds at 750 °C for two hours decreased the hardness of the unshielded 23J/mm and 50J/mm welds by about 30 HV units. In the case of the 90 J/mm weld the reduction in hardness was 10 HV units. A comparison of the hardness of the shielded and unshielded welds suggests the presence of martensite in the unshielded samples. This means that the austenite loop must broaden quite lot by the influence of nitrogen of the air. According to the Balmford et al. diagram the nitrogen content of this steel needs to rise above 0.18 % for martensite formation. On the other hand during the rapid cooling process there is not enough time for N2 and C to be precipitated which can increase the free C and N2 content (Lee et al., 2008 and Balmford et al., 1998).

Even after heat treatment the unshielded welds retained a higher hardness, which indicates that the hardness of these welds is to some extent due to the presence of hard oxides rather than martensite. Also, according to Lakshminarayanan the high hardness of the laser weld can be a result of the very fine solidification structure produced (Lakshaminarayanan et al., 2012).

4.2. Tensile properties

All the tension test specimens failed in the base material, indicating that the tensile strength of the welds was at least equal to that of the base material.

4.3. Formability properties

The formability of the all unshielded welds was very poor regardless of welding energy. Heat treatment at 750 °C for 2 hours increased the formability of unshielded welds a little, but the formability remained rather poor (see table 5 and figures 10 and 12). The formability of the welds which were welded by using argon shielding gas was very good regardless of welding energy. According to this the higher hardness of the weld does not have as harmful an effect as was expected. In the study made by Lakshminarayanan et al. the helium shielded AISI 409M laser welds failed in a ductile manner in tensile and impact tests despite the hardening of the weld (Lakshaminarayanan et al., 2012). The Erichsen test results in fig. 9 also showed very clearly the differences between shielded and unshielded welds. The argon shielded 90 J/mm welds were as formable as the base material whereas the unshielded welds were broke down rapidly at quite low strain values.

The main reason for the brittleness of the weld seems to be the presence of hard oxides which have a deleterious effect on the weld.

4.4. Microstructure

Microstructural examination found no martensite in the microstructure of any of the welds. Therefore the reduction in hardness of the unshielded welds decreases during the heat treatment was probably due to the release of residual stresses around the oxide precipitations in the ferritic matrix.

5. Conclusions

The welding energy of keyhole laser welding is usually enough low to achieve an acceptable toughness in welds made in ferritic steels as long as adequate Argon shielding is employed. It is very important to take care of good gas shielding of the ferritic stainless steel weld.

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